

Perspective

# Toward a definition of Essential Mountain Climate Variables

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## SUMMARY

The numerous processes implicated in the rapid and profound climate-driven changes that are underway across the world's mountains must be well monitored, understood, and—as far as possible—accurately projected. However, not only are the available environmental data upon which such activities hinge often severely limited, but interdisciplinary consensus regarding which variables should be considered observation priorities also remains elusive. Here, the concept of Essential Mountain Climate Variables (EMCVs) is introduced as a potential means of ameliorating the situation. After a review of climate-driven environmental change in mountains, a preliminary set of corresponding EMCVs is proposed. Variables pertaining to several disciplines naturally feature prominently. In addition, several are not currently considered to hold broader global relevance, which justifies our mountain-specific approach. Established and emerging possibilities to measure, generate, and apply EMCVs are then summarized. Finally, future activities toward the concept's formalization are recommended. Ultimately, the approach hopes to increase the utility of mountainous environmental data to both fundamental science and decision making related to environmental management, risk mitigation, and adaptation.

## INTRODUCTION

Mountainous regions provide numerous ecosystem goods and services to human populations both within and downstream of their boundaries including water, hydropower, and timber, as well as settings for leisure and tourism-related activities.<sup>1</sup> However, as a result of ongoing general climatic warming trends, many of the environmental system components from which these goods and services derive are evolving rapidly, often with adverse consequences. Some of these changes, such as the widespread retreat of mountain glaciers<sup>2,3</sup> and declining trends in seasonal snow depth, extent, and duration,<sup>4,5</sup> are profound and highly visible. Others—the responses of vegetation, permafrost, and biodiversity, for instance—tend to be somewhat slower and more subtle but are nevertheless still detectable.<sup>6–9</sup> In some aspects of mountainous environmental systems,

including ecosystems, it is likely that critical “tipping points” are rapidly being approached.<sup>10,11</sup>

Under these circumstances, authorities and other stakeholders with decision-making responsibilities are reliant upon the scientific research community to deliver robust predictive models that are capable of supporting the design and implementation of appropriate forward-looking mitigation, adaptation, intervention, and environmental management strategies. The development of such models requires the possession of sound conceptual understanding and thus the availability of sufficiently broad, informative, and representative environmental data. In mountainous environments, however, many challenges are typically encountered when one seeks the necessary data, most notably difficult access, harsh conditions, and the considerable diversity and high spatiotemporal variability of phenomena. Moreover, many important system components are intrinsically

linked with one another via a series of complex process interactions and feedback mechanisms. Consequently, highly interdisciplinary or even transdisciplinary perspectives are often required.

Although significant advances in remote-sensing technologies have been made of late, they are not a panacea in mountainous terrain; as shall be explained more fully shortly, *in situ* observations retain a crucial role in many regards. As such, pragmatic decisions regarding which variables should be prioritized for measurement and conversely which should not (i.e., where limited resources are best invested) are still routinely required, and this situation is likely to persist for many years to come. At present, priorities tend to be established in a fairly *ad hoc* fashion according to the needs of individual projects or programs, leaving a data landscape that is rather fragmented and heterogeneous and that exhibits little global commonality. Specifically, interdisciplinary consensus regarding which variables are most crucial for better monitoring, understanding, and ultimately predicting the most important aspects of climate-driven mountainous environmental change globally—and how they can be obtained in a systematic, intercomparable way—remains lacking.

If a standardized set of environmental variables that are generally recognized to be the most informative with regard to dominant or critical aspects of climate-driven mountainous environmental change, plus associated minimum observation requirements and strong open data-sharing policies, could be identified and agreed upon by the global mountain community of researchers, practitioners, and policymakers, it should be possible to compile a globally intercomparable database of diverse but consistent and useable evidence. Many potential applications of such a database—spanning a range of disciplines and spatial scales—could be envisaged, many of which could be highly impactful.

This perspective brings together the experience of an interdisciplinary group of mountain researchers to propose a concept that could help address this broad challenge, as well as to communicate several steps that have already been undertaken toward this objective. After briefly providing some more specific examples of applications that could benefit from such an initiative, we outline the background to our proposed solution. The main components and most important processes operating in mountainous environments—including associated ongoing or projected climate-driven changes—are then briefly reviewed from the perspectives of four major components of mountainous environmental systems; this review serves as a basis for the identification of a preliminary list of candidate priority variables, which are ranked according to their perceived importance. Thereafter, an overview of both established and emerging approaches and techniques for measuring or otherwise deriving some of the identified variables is provided. In closing, certain additional steps that could contribute to the eventual formalization and uptake of the concept are proposed before conclusions are drawn.

## THE NEED FOR INTERDISCIPLINARY OBSERVATIONS

As stated above, the availability of consistent, informative, and interdisciplinary environmental observations in mountains is

paramount, *inter alia*, to developing sound conceptual understanding of complex mountainous systems and—by extension—generating reliable and useful predictions pertaining to them. To illustrate this point, the concept of elevation-dependent warming (EDW)<sup>12,13</sup> or—more broadly—elevation-dependent climate change (EDCC) is briefly considered.

EDW or EDCC is the notion that climatic changes could be occurring faster (and hence their impacts being felt more keenly) in higher-elevation or mountainous areas than in adjacent lowlands. Systematic variations in rates of warming with elevation have now been observed in many regions.<sup>14</sup> However, the mechanisms that bring about these effects, including their respective contributions and potential interactions, remain imperfectly understood. Several processes could be involved:

1. The snow albedo effect, whereby the loss of snow and ice due to increasing temperatures—particularly around typical snowline elevations—leads to amplified warming at higher elevations via a positive feedback mechanism.<sup>15–17</sup>
2. Increased atmospheric vapor pressure could preferentially increase downward longwave radiation and therefore enhance warming at high elevations.<sup>18,19</sup>
3. The increased deposition of light-absorbing aerosols (black carbon, organic carbon, or desert dust) on snow or glacier ice can reduce the albedo of the land surface, further enhancing snow and ice melt and subsequent warming,<sup>20</sup> although in some areas, increases in low-elevation incoming shortwave radiation associated with decreases in aerosols and clouds can counteract this effect, perhaps even reversing temperature-elevation gradients entirely.<sup>21</sup>
4. Increased atmospheric moisture content can cause atmospheric lapse rate profiles to become shallower (i.e., air temperature decreases less sharply with increasing altitude); this effect can be especially important in the tropics.<sup>22</sup>
5. A given shift in radiative forcing induces larger air temperature changes in cooler conditions (which are common in mountains) than in warmer environments via the Stefan-Boltzmann effect.<sup>23</sup>
6. Elevation-dependent changes in land cover associated with the systematic migration of vegetation species<sup>11,24</sup> and the advancement of upslope movement of tree-lines<sup>25,26</sup> again influence surface albedo, energy flux partitioning, and ultimately climate in an elevation-dependent fashion.<sup>27</sup>

Considered together, these processes evidently act both within and across multiple different components (or “spheres”) of the Earth system in general and mountainous environmental systems more specifically, including the atmosphere (processes 2–5), cryosphere (1 and 3), biosphere (6), and hydrosphere (1, 2, and 4). Consequently, developing improved understanding of EDCC will require the analysis (and perhaps also the integration, for example, into sophisticated numerical models) of a large quantity of reliable, consistent, long-term, and intercomparable observational data pertaining to several traditionally distinct disciplines. Note that in this context, “improved understanding” could mean being able to attribute observed changes to their

underlying causal mechanisms and thereby assessing the relative importance of each, including any associated geographical and temporal variability thereof.

EDCC represents but one example, however. A host of other mountain-related applications require, or at least would benefit from, more diverse, consistent, and timely environmental data. Many could be more “direct.” For instance, such observations are needed to help inform policy-oriented assessment exercises, including those conducted at a global level under the auspices of organizations such as the Intergovernmental Panel on Climate Change and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. They are likewise necessary for reporting regularly and confidently on the situation in mountainous environments with respect to targets prescribed by global policy agendas, such as the UN 2030 Agenda for Sustainable Development and the Sendai Framework for Disaster Risk Reduction. Observations can furthermore contribute to the design or iterative refinement of such policy instruments, from the global to the local level, such that their relevance, feasibility, and effectiveness are maintained. Clearly, being able to draw upon a certain fundamental level of uniformity and informativeness in the data from mountainous regions globally in support of such tasks would be extremely beneficial.

Looking ahead, empirical observations also contribute greatly to the development of regional- and local-scale future climate projections, upon which most climate policy, adaptation, and mitigation measures are ultimately founded. For instance, they inform statistical downscaling or provide information for model evaluation. Observations are likewise critical to so-called climate impact models, which seek to translate potential climate change scenarios into plausible impacts on aspects of the mountain cryosphere, biosphere, and hydrosphere. In this sense, historical observations provide the necessary data for forcing and constraining such models so they can be subsequently applied with some confidence in predictive mode. Although attention must be paid to avoid overfitting, employing historical observations that are as reliant, informative, and consistent as possible in terms of their spatiotemporal coverage, resolution, and accuracy should minimize the impact of any inconsistency in such “data characteristics” on the uncertainty associated with the model predictions and hence maximize the robustness of any subsequent decisions or interventions made on their basis.

It follows that any deficiencies in the existence, discoverability, accessibility, quality, length, consistency, representativeness, and usability of observational data can severely impinge upon numerous important tasks that must be completed across the science-policy-practice continuum in relation to the state of mountains under climate change. However, in such terrain, many existing deficiencies are fairly deeply embedded and thus challenging to overcome, although there are of course differences according to specific variables and regions. The principal issues that typically limit the quantity, quality, and spatial representativeness of *in situ* data that can be obtained have already been summarized, but they are worth briefly reiterating and slightly expanding upon slightly here. The first is the comparative inaccessibility and inhospitality of mountainous terrain. The second is the considerable number, complexity, diversity, and spatiotemporal variability of physical processes that are encountered; for instance, much of the spatial variability in environ-

mental conditions and processes that one typically encounters in mountainous settings is driven by the complex, rugged topography. Thirdly, limited funds and technical capacities represent further constraints in many regions.

Consequently, for reasons of practicality and cost, meteorological stations (for example) are often preferentially situated in valley bottoms as opposed to on mountain slopes and summits. Their spatial distribution is therefore biased, which affects their capacity to characterize the pronounced variability that spatial fields of meteorological variables—perhaps precipitation above all—often exhibit in elevated, complex terrain. Furthermore, even if a dense and even coverage of stations could be attained, technical challenges associated with typical mountain conditions can affect measurement quality or accuracy. For instance, as a result of gauge undercatch, which is heavily accentuated in snowy and windy conditions, precipitation totals are often severely underestimated.<sup>28</sup>

Technological advancements are undoubtedly helping to address many of these traditional challenges. For example, with the advent of new cosmic ray sensors, soil moisture can now theoretically be measured *in situ* over reasonably large integrated areas rather than merely at point locations.<sup>29</sup> Perhaps even more importantly, satellite remote sensing has vastly increased the availability of data pertaining to certain variables. For instance, snow extents and vegetation cover can now be retrieved routinely at moderate to high spatial resolutions from free and open data provided by organizations and services such as NASA and Copernicus. Indeed, this rapid progress in remote observation technologies and retrieval methods provides one strong argument for the need to rapidly converge on common standards and thus generate more consistent and interoperable data products in the future. For variables that can be measured both remotely and *in situ*, the contrasting characteristics of these data sources, especially with respect to spatial versus temporal coverage, often make them highly complementary.

For several other variables that are important in mountains, however, it remains impossible to derive any data at all, or else data with the requisite spatiotemporal resolution, coverage, and/or accuracy such that they are likely to be useful in mountainous applications, via remote sensing. Given such technical constraints and limited resources for monitoring activities, pragmatic decisions regarding which variables to focus on measuring *in situ* or otherwise deriving are likely to be required for many years to come. Establishing a set of interdisciplinary variables that, together, could provide a broad overview of ongoing climate-driven mountainous environmental change should enable monitoring resources to be invested more optimally. Over time, more consistent and long-term datasets pertaining to these variables will hopefully emerge. In addition, because a certain amount of change has already been realized, these “priority” variables could also form foci for attempts to intelligently extract maximal value from existing datasets, thereby retrospectively generating improved datasets.

In summary, defining such a set of priority mountain climate-related environmental variables and their associated attributes or “observation requirements” (which should be met to ensure usefulness) should enable fairer comparisons to be made across global mountain regions, contribute to answering many

increasingly urgent scientific questions, and meet various policy needs. Below, a framework to support these tasks is proposed. Four specific questions are considered:

1. What are the main components of mountainous environmental systems and their associated dominant climate-related drivers, processes, and impacts of ongoing and potential future change?
2. Which specific corresponding variables should be observed as a priority for better understanding the mechanisms involved and their impacts, generating more reliable future predictions, and providing consistent data for reporting?
3. What current and emerging possibilities exist for measuring or otherwise obtaining data on these variables?
4. What additional steps should or must be completed if the concept is ultimately to be formalized?

## PROPOSED SOLUTION: EMCVs

### Background and guiding philosophy

To address the challenge(s) outlined, we propose the establishment of a set of so-called Essential Mountain Climate Variables (EMCVs). This approach builds upon the established concept of Essential Climate Variables (ECVs), which has already gained considerable traction.<sup>30</sup> Essentially, the establishment of ECVs and their associated observation requirements intends to ensure that, irrespective of their sector, all data users have access to the necessary basic observational data for addressing climate-related issues at a global level.

The definitive set of ECVs is curated by the Global Climate Observing System (GCOS; <https://gcos.wmo.int/>), which defines ECVs as “physical, chemical or biological variables or a group of linked variables that critically contributes to the characterization of Earth’s climate” that “provide the empirical evidence needed to understand and predict the evolution of climate, to guide mitigation and adaptation measures, to assess risks and enable attribution of climate events to underlying causes, and to underpin climate services.”<sup>31</sup> “Climate” here is a broad concept encompassing not only meteorological and climatic variables but also variables corresponding to climate-related processes and impacts in other system components, such as the cryosphere, hydrosphere, and biosphere. This inclusive definition is maintained here.

However, the existing concept must be modified in several regards so it can be rendered applicable in mountainous contexts (cf. Milosavljevic et al.<sup>32</sup>). Certain ECVs—such as those related to the oceans—are largely irrelevant in mountainous areas. Other variables could be considered of insufficient global importance to feature as ECVs but could be critical in the mountainous regions. For these reasons, our new mountain-specific framework is not constrained to the current set of ECVs (i.e., variables can be readily added or removed).

In addition, although some variables that could be considered essential in mountainous contexts might share a name with an existing ECV, the specific attributes with which measurements of such variables must be endowed to be useful in the mountains (henceforth, “observation requirements”) might differ substantially. For example, higher spatial resolution will most likely often

be necessary for many variables in mountainous contexts to capture the effects of elevated and rugged topography. The specification of mountain-specific observation requirements will therefore require careful and dedicated discussion.

For a given variable to be included as a general ECV, not only should it be relevant (i.e., provide useful insight into the Earth’s climate and its changes), but its measurement should also be technically and economically feasible with standard technologies. EMCVs are also strongly rooted in remote sensing and empiricism. In this regard, in proposing our mountain-specific framework, we advocate for certain additional divergences from the established framework. First, the requirements for technological and economic feasibility are relaxed. As such, being independent of current sensor capabilities and other technical and practical considerations, the list of EMCVs arrived at could be somewhat aspirational. In some ways, this could amount to prioritizing, or at least highlighting, difficult scientific problems and technical measurement challenges rather than focusing merely on more routine applications of existing technologies. Second, with the unique challenges posed by mountainous terrain, our new concept is not limited to predominantly remotely sensed datasets. Rather, equal emphasis is placed on *in situ* observations, as well as possibilities to integrate observations from various sources with a range of algorithms and numerical models to generate both more spatiotemporally comprehensive and accurate historical datasets and more reliable future predictions.

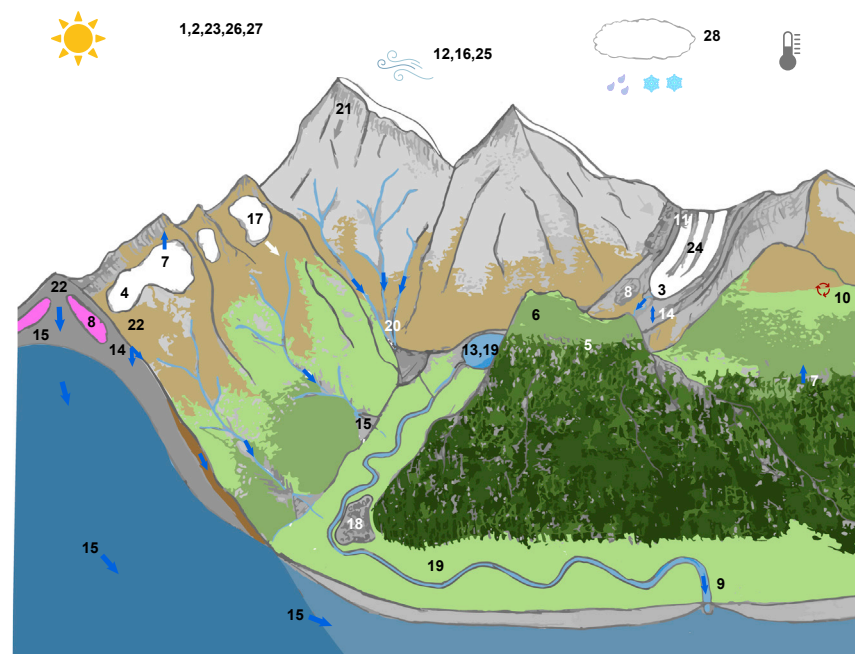
Thus, the concept of EMCVs is proposed. EMCVs can tentatively be defined as “physical, chemical or biological variables that either currently do, or potentially could, significantly contribute to the characterization of Earth’s mountainous environmental systems, especially under climatic change.” At this stage, our intention is merely to develop and present a preliminary set of candidate EMCVs that are ranked according to their perceived importance across disciplines rather than a firm, prescriptive classification of essential (and by extension non-essential) variables. This is consistent with our appreciation of the fact that, although as broad and inclusive a position as possible is taken, the particular constitution of the assembled group of authors, as well as the process followed (see [experimental procedures](#)), could have influenced the outcome somewhat.

Further work beyond this contribution will be required if the concept of EMCVs is eventually to become formalized and widely implemented. As such, our intention here is to stimulate discussion and debate among the broader mountain research community regarding the approach in general and the variables and their associated requirements more specifically. Finally, it is worth mentioning that, depending on its eventual scope, it is possible—even probable—that certain individual applications will require observations of variables that fall beyond this “essential” list, or else they must meet very particular observation requirements. These applications should theoretically be fairly specific, however, that is, hold less general relevance across disciplines, processes, and regions.

### Identifying key aspects of environmental change

Existing knowledge of the key components of mountainous environmental systems in general—and the drivers, processes, and impacts of climate-related change more specifically—must be summarized and presented in an integrated sense before one





**Figure 1. The main components of mountainous environmental systems and associated change processes that are either already in course or are expected to be realized in many global mountain regions in the future**

Such systems are typically underpinned by rugged topography and often complex consolidated and unconsolidated geological architectures. Being highly interconnected, changes in individual components and processes are likely to propagate widely, potentially inducing either positive (i.e., reinforcing) or negative (i.e., limiting) feedback mechanisms. (1) Increasing atmospheric greenhouse gas concentrations; (2) shifts in the radiative forcing, air temperature, and precipitation (including precipitation intensity and, where applicable, rain/snow ratios); (3) increasingly negative glacier mass balance or glacial retreat (changing albedo and water storage); (4) changing snow dynamics (changing albedo and water storage, potentially also affecting vegetation); (5) rising treelines (changing albedo); (6) increased species richness or biomass on mountain summits; (7) changing evapotranspiration and sublimation dynamics; (8) permafrost and rock glacier thaw; (9) changing streamflow dynamics (including source component contributions); (10) accelerated nutrient cycling between the atmosphere, soil, and vegetation; (11) changes in glacier debris cover (changing albedo); (12) changes in the atmospheric

transport and deposition of dust, aerosols, and black carbon; (13) changing lake water temperatures and ecology; (14) changing hydrological partitioning at the land surface and surface-water-groundwater exchanges more generally; (15) changing groundwater recharge, storage, flow, and discharge dynamics in bedrock and unconsolidated aquifers (e.g., alluvial fans, talus slopes, and moraines), including MBR and mountain front recharge; (16) changing redistribution of snow by wind; (17) changing avalanche hazard; (18) changing flood hazard (pluvial, fluvial, and glacial lake outburst); (19) increasing drought frequency and severity; (20) changing erosion, sediment transport, and deposition dynamics, and debris flow hazard; (21) increasing slope instability and rockfall hazards; (22) potential release of carbon from frozen mountain soils; (23) changing atmospheric vapor pressure; (24) changing glacier flow rates; (25) increasing transport of anthropogenic ozone precursors and subsequent elevated impacts on the biosphere; (26) change in near-surface air-temperature lapse rates and orographic precipitation gradients; (27) changing synoptic weather patterns; and (28) changes in cloud cover and cloud radiative forcing. Note that this figure is not intended to be exhaustive but rather aims to serve as a basis for the subsequent discussion, identification, and ranking of potential EMCVs.

can proceed to evaluate whether or not any individual variables could be of sufficient interdisciplinary importance to be specified as priorities for routine and consistent monitoring or derivation across mountain regions globally (i.e., should be considered EMCVs). In the four sub-sections below, mountainous environmental systems are briefly considered from the perspectives of their four main constituent “spheres,” or disciplines, in turn. This is neither an exhaustive nor a systematic review, although attempts are made to be as comprehensive as possible. In particular, some of the important links between disciplines are highlighted (see also Figure 1).

### Atmosphere

Through their impact on Earth’s energy balance, increasing atmospheric greenhouse gas (GHG) concentrations—which are largely a result of fossil fuel combustion and other activities—<sup>33</sup>are the main driver of anthropogenic climate change.<sup>34</sup> Their effects on atmospheric temperatures and precipitation patterns, including through large-scale feedbacks involving atmospheric moisture and circulation, are responsible for many of the changes that are taking place across the world’s mountainous environmental systems.<sup>14</sup> In general, processes related to large-scale atmospheric dynamics and upper atmospheric variables are already quantified and simulated by the global atmospheric community. This discussion therefore predominantly focuses on certain specific atmospheric pollutants that can have direct effects on mountainous environmental systems at finer spatial scales.

Tropospheric ozone is a short-lived GHG that directly affects human health and ecosystems.<sup>35</sup> Because of its fairly high reactivity, the spatial variability of its atmospheric abundance is considerable. Mountain regions are particularly vulnerable to the direct impacts of ozone because of stratospheric intrusions, which transport ozone-rich air masses to the ground, as well as emissions of anthropogenic ozone precursors in upwind urban areas. In turn, such phenomena could affect the growth, productivity, and phenology of the biosphere.<sup>36</sup>

Deposition of airborne aerosols of anthropogenic (e.g., black carbon) and natural (e.g., mineral dust) origin, meanwhile, has major implications for the albedo of snow- and ice-covered surfaces in mountainous regions. Such deposition decreases surface albedo, which leads to increased absorption of solar energy. In turn, this can exacerbate melt,<sup>37</sup> potentially altering melt-water generation and runoff patterns. Atmospheric circulations acting on various spatial scales influence the transport of such aerosols into mountainous regions. For instance, valley circulation can transport local or regional emissions to higher altitudes,<sup>38</sup> whereas synoptic systems are able to transport mineral dust and emissions arising from fossil fuel combustion, biomass burning, and open fires in distant source regions.<sup>39</sup> Van Marle et al.<sup>40</sup> reported that long-term patterns in fire carbon emissions vary greatly by region, illustrating that changes in both emission (or re-suspension) rates and atmospheric circulation patterns can influence the deposition of light-absorbing aerosols upon the mountain cryosphere.

The presence of absorbing aerosol layers in the atmosphere can also affect vertical temperature gradients, whose implications for atmospheric circulation and cloud formation could initiate a feedback loop to the larger atmospheric circulation system. Somewhat more locally, Letcher and Minder<sup>41</sup> suggested that warming-induced changes to the snow albedo feedback, to which aerosol deposition might contribute, could enhance up-slope winds.

### **Cryosphere**

Snow, glaciers, lake ice, and permafrost are prominent in many mountainous regions. Mountain snowpacks, glaciers, and permafrost have decreased in extent and mass over recent decades and are projected to continue to do so.<sup>14</sup> Such changes are intimately linked with other “spheres” in that they are driven by changes in the atmosphere, affect the local biosphere adapted to snow and ice, and drive downstream changes in the hydrosphere. Reductions in the seasonal storage of water in the form of snow, and the loss of non-renewable glacial ice, have the potential to strongly affect water resources.

The high albedo and low thermal conductivity of snow act to cool the snow surface and keep the subsurface warmer than it would be under snow-free conditions. Although both total precipitation and the fraction falling as snow tend to increase with elevation in mountains, snow redistribution by wind and avalanches can result in diminished accumulations at the highest and most exposed elevations.<sup>42</sup> Glacier mass accumulation is fed by snowfall, drifting snow, and avalanches.

In many regions, climatic warming—possibly alongside increased deposition of anthropogenic aerosols, as highlighted above—is leading to reductions in snow cover and, via the positive snow albedo feedback mechanism, further warming. This amplification effect is therefore likely to be strongest at elevations where spring and summer snowlines are retreating. Variations in the hypsometric distributions of elevation between different mountain catchments and regions will also influence the degree of aerial snow cover reduction.

Although mountain glacier recession has been widely observed,<sup>43</sup> temperatures permitting, some glaciers can advance despite warming if snowfall also increases. Glacier flow rates can either decrease as a result of thinning or increase as a result of increased lubrication by meltwater and surge instabilities. Debris cover on glaciers can reduce local melt rates but exert a complex influence on overall glacier mass balance.<sup>44</sup>

According to the limited direct subsurface observations that can be obtained, mountain permafrost appears to be warming and degrading under the influence of increasing air temperatures and changes in snow-cover insulation effects.<sup>6</sup> In narrow mountain ridges, permafrost can thaw from both sides simultaneously. The amount of carbon frozen in mountain soils that could be released to the atmosphere by thawing is highly uncertain.<sup>45</sup>

Cryosphere changes in mountains are also associated with various natural hazards, including glacial lake outburst floods, thaw-induced slope failures (e.g., rockfalls and landslides), and, potentially, altered avalanche regimes.<sup>14</sup> In the assessment of risk, the growing human and societal exposure to cryospheric (and other) hazards, which is related to the increasing socio-economic development of many mountain regions, must be considered alongside potential changes in hazard event frequency and magnitude. That said, the socio-economic variables required for

quantifying exposure in mountain environments fall beyond our present focus.

### **Biosphere**

In the free atmosphere, air temperatures decrease on average by 5.5 K per kilometer of elevation gained.<sup>46</sup> A marked zonation of plant life forms and vegetation types is therefore evident in mountainous regions.<sup>47</sup> At species' upper elevational limits, temperature-related factors can cause physiological limitations, such as reproductive failure, growth reduction, or the death of tissues or individuals. Such factors often act on species occurrence in a threshold-like fashion. At species' lower range limits, biotic interactions and water conditions are generally more important.<sup>48</sup>

Two striking upper range limits are found along the elevational gradient in mountains: the treeline and the grassline. The former, defined as the transition from potentially forested to treeless terrain, is the most prominent. Its location can be determined empirically through delineation, from climatic data, of where the minimum growing season length is 94 days and the mean growing season soil temperature is approximately 6.4°C.<sup>49,50</sup> Indeed, as a result of strong coupling between atmospheric and near-surface thermal conditions in the summer, the (climatic) treeline can typically be reasonably well approximated from basic measurements of air temperature, provided that aridity does not interfere. In contrast, low-stature shrub- or grass-type vegetation between the treeline and the grassline is at least periodically decoupled from ambient atmospheric conditions in that it actually often experiences substantially warmer microclimates than interpolated air-temperature data from meteorological stations would suggest.<sup>51</sup>

Where low-stature vegetation is not sheltered by tree canopies, additional factors such as moisture, solar radiation, and wind become more influential<sup>46</sup> and contribute to local “topoclimate.” For instance, variations in solar radiation affect not only surface energy budgets and temperatures but also soil moisture conditions. Alpine and montane deserts can arise where trees and other vegetation are absent as a result of a lack of moisture. However, in temperate mountains, total precipitation generally increases with elevation.<sup>52</sup> This, together with the lower evaporative demand produced by the low air temperature at higher elevations, results in an altitudinal decrease in conditions leading to water stress.<sup>53</sup> In arid zones, water stress gradients can be considerably more complex such that drought stress is possible at both low<sup>53</sup> and (especially with increased glacier loss) high elevations.<sup>54,55</sup>

Recent temperature increases have been associated with increased vegetation cover and diversity on mountain summits globally.<sup>56</sup> Increased plant species diversity is currently most visible in the alpine vegetation zone<sup>57</sup> and can be attributed to decreasing competition and the increasing availability of space at higher elevations for colonizers. A longer and warmer growing season has also already enabled high-elevation plant communities to produce more biomass<sup>58</sup> and colonize habitats where long-lasting snow cover previously prevailed; in snow-driven ecosystems, years with limited snow-cover duration are linked with increased soil temperatures and growing season microbial biomass, which accelerate vegetation growth and raise productivity.<sup>57</sup> Greening dynamics might have slowed of late, however.<sup>58</sup>

In another rapid response of vegetation, the difference in the phenological stage of tree species with elevation is diminishing, partly as a result of strong phenological advancement at high elevations.<sup>10,59</sup> This trend is most likely related to warmer winter temperatures and stronger warming at high elevations during late spring in many locations.

So far, treelines mostly exhibit only evidence of recruitment at higher elevations.<sup>26</sup> That said, most alpine treelines are expected to (even inevitably will) respond to ongoing climate change by shifting upward from their current positions<sup>26</sup> such that trees are jeopardizing the distribution of heliophytic and orophyte species (i.e., low-stature and alpine plants). In mountain landscapes influenced by human land-use histories, detecting climate-induced treeline shifts can be difficult because pasture abandonment can simultaneously drive shifts.<sup>25,60</sup> Forests could offer some protection against avalanches and rockfalls.

The increasing frequency of drought conditions can weaken mountain forests, and warmer temperatures can promote parasite development<sup>61</sup> with the potential to induce positive (i.e., reinforcing) feedbacks with negative implications.<sup>62</sup> Interactions and feedbacks between vegetation and the alpine soil microbiome are also relevant for understanding and predicting changes in mountain ecosystems. The soil microbiome plays several vital roles in the processes of pedogenesis, biogeochemical cycling, and the colonization of bare soils by plants.<sup>63</sup> Microbial diversity in alpine soils is influenced by elevation<sup>64</sup> and has been shown to respond sensitively to warming, accelerating carbon and nitrogen cycling.<sup>65</sup>

### Hydrosphere

The mountain hydrosphere is likewise heavily influenced by other “spheres.” As mentioned above, orographic effects generally enhance cumulative precipitation totals in mountainous regions, whereas in temperate regions the release of water stored temporarily in the form of snow and ice is characteristically delayed. Thus, outside the tropics, mountain streams and rivers exhibit distinctive annual flow regimes (discharge is an important catchment-integrated metric). Evapotranspiration ( $ET_a$ ) generally decreases strongly with elevation as a result of decreasing atmospheric demand, although vegetation characteristics and moisture availability can modulate these patterns. Still, mountain catchments often exhibit relatively high runoff ratios. Reflecting this, mountains are often referred to as “water towers.”<sup>66,67</sup> The respective contributions of liquid precipitation and snow- and ice-melt inputs to terrestrial mountain catchment systems depends heavily on geographical region and catchment elevation (distribution).

Soil hydraulic properties exert a strong influence on hydrological partitioning at the land surface. Meanwhile, large hydraulic gradients associated with steep topography drive comparatively high-velocity surface and subsurface flows and additionally favor pronounced interactions between surface water and groundwater. Furthermore, the unconsolidated and consolidated geology of mountainous regions is often inherently complex, and in many geological settings (e.g., where unconsolidated sediments are predominant, in catchments underlain by fractured crystalline bedrock, in calcareous regions, and so forth), the spatial distribution subsurface hydraulic properties can strongly affect broader hydrological system functioning.<sup>68–70</sup>

Driven primarily by changes in air temperatures (with respect to accumulation phase, snow and ice melt, and evapotranspiration demand) and precipitation inputs, future changes in internal catchment hydrological processes will combine to modify the total annual discharge, flow level quantiles, and seasonality of mountain-originating watercourses. It should be noted that future temperatures can be projected with far greater confidence than can precipitation (for which, depending on the region, climate models might not even agree on the overall sign of change).

Permafrost thaw could influence the partitioning of water near the land surface (favoring deeper, longer subsurface flow pathways), which could flatten hydrographs (i.e., lower peaks and raise baseflows).<sup>71</sup> Evaporative losses are also likely to increase in many non-water-limited systems not only because of changing climate<sup>72</sup> but also because of the indirect effects of vegetation expansion. Floods represent a major hazard in many steep mountainous regions, whereas erosion, sediment transport, and deposition are additional landscape-shaping processes that are often hydrologically controlled.

### Integrated system

Figure 1 attempts to represent the current understanding of the main components of mountainous environmental systems and their associated (either currently ongoing or else foreseen) climate-related changes in many regions. To our best knowledge, no such rather comprehensive representation of integrated mountain systems has previously been presented in the literature.

Some of the interactions between system components shown in Figure 1 are fundamental and act irrespectively of any change in external forcing. For instance, steep and rugged mountain topography affects a multitude of processes and characteristics, including patterns of snow accumulation, redistribution (via wind and gravity), and melt; local-scale meteorology (e.g., via rain shadowing and modifying local wind fields); mass movement hazards; hydraulic gradients; and hydrological connectivity. Similarly, aspects of vegetation and hydrology such as soil moisture conditions and depths to groundwater have been shown to evolve co-dependently.<sup>73</sup> Bedrock lithology affects its erodibility and hence landform topography, as well as the availability of substrate for pedogenesis. Vegetation (especially forest) makes an important contribution to soil fixation and preservation.

Other interactions and feedbacks become more active or pronounced under strong external change (e.g., climate change). For instance, alongside the snow albedo feedback and other mechanisms discussed earlier in relation to EDCC, changing avalanche activity will modify patterns of meltwater arrival at the land surface, whereas glacial retreat can lead to over-steepened slopes, generating a feedback to topography.

### Identifying and ranking potential EMCVs

After this review, a preliminary set of potential EMCVs were identified and ranked according to a consensus view of perceived importance (for methodological details, see the [experimental procedures](#)). In total, 97 variables were considered to be at least somewhat important for monitoring and/or understanding key mountain processes pertaining to one or more system components (i.e., were assigned a score  $\geq 1$ ). Table S1 presents the refined and consolidated outcome of this exercise in full.





**Table 1. Potential EMCVs that could be considered “uniquely essential” in mountainous contexts (i.e., variables that are considered important in mountains but are not stipulated as globally relevant ECVs by GCOS)**

Principal sphere(s)	EMCVs
Biosphere and hydrosphere	evapotranspiration
Atmosphere	nitrogen deposition
Biosphere	vegetation species abundances and extents
Atmosphere	<i>in situ</i> ozone concentration
Biosphere	geomorphological or avalanche perturbation of vegetation (spatial extents)
Cryosphere	glacier debris cover (extent and thickness) and dust deposition on snow and ice
Atmosphere	<i>in situ</i> aerosol absorption
Atmosphere	<i>in situ</i> aerosol scattering
Atmosphere	near-surface air-temperature lapse rates and orographic precipitation gradients
Biosphere	forest extent
Cryosphere	snow microstructure
Atmosphere and cryosphere	black carbon deposition
Atmosphere	geopotential height
All	upward longwave radiation flux
All	upward shortwave radiation flux
All	natural hazard maps
All	spatially distributed topographic data
Hydrosphere	mountain front recharge
Hydrosphere	mountain block recharge
Hydrosphere	glacier melt (also known as runoff)
Hydrosphere	snow melt (also known as runoff)
Hydrosphere	stable isotopic composition of water (snow, rain, glacier ice, surface, and groundwaters)
All	past natural hazard event extents and intensities
Hydrosphere	dynamic groundwater storage
Hydrosphere	soil hydraulic properties
Hydrosphere and biosphere	soil thickness

are more mountain specific and so have less correspondence with existing ECVs. For example, upward radiation flux, *in situ* ozone, and snow microstructure relate to the needs that were identified to thoroughly characterize the energy balance (implicitly including the effects of factors, such as slope aspect and topographic shading), local atmospheric conditions, and other relatively small-scale but influential factors in mountainous terrain.

Because many of these variables are arguably best monitored *in situ*, it is conceivable that they might have been comparatively overlooked when ECVs were defined simply because the GCOS framework generally places greater emphasis on remotely

sensed data sources (although some variables that are normally measured *in situ*, such as river discharge, are included as ECVs). Some of these variables could also not have been considered by GCOS because their direct measurement might not be straightforward with current technologies (e.g., they might rely more on simulation approaches, as in the case for snowmelt and mountain block recharge [MBR], for example).

Elevation data and derivable topographic metrics, such as slope, aspect, and ruggedness, often form fundamental inputs to a range of spatial analyses and numerical predictions of mountainous environmental phenomena. For this reason, spatially distributed topographic data—which are generally readily available and with ever improving resolution and accuracy<sup>74</sup>—were also proposed as an additional variable group.

Our set of proposed EMCVs also includes variables pertaining to climate-related mountainous natural hazards, which are presently not considered ECVs; reliable information on these variables is often lacking but will certainly play a key role in supporting sustainable development and mitigating and managing risk in mountains regions (including through transfer mechanisms, such as insurance) over the coming years and decades.

Finally, some of the additional variables identified as being important in mountains specifically might in fact have a broader (and perhaps somewhat underestimated) relevance more widely, including in cases possibly even globally. Variables under this category could include those that enable the explicit quantification of the respective contributions of evapotranspiration and sublimation to moisture transfer from land surface to the atmosphere, snowmelt, the deposition of dust and black carbon on snow and ice (including in polar regions), soil properties, stable water isotope measurements, and the contribution of groundwater to the recharge of unconsolidated aquifers in adjacent lowlands via mountain front recharge and MBR. It could be appropriate to consider some of these “mountain-unique” variables for inclusion in the main GCOS set of ECVs in the future.

## MEASURING EMCVs

### Established approaches

Some established approaches for measuring or otherwise deriving selected potential EMCVs, along with relevant associated organizations and initiatives working on their collation and curation, where applicable, are briefly summarized below. The material is organized according to the disciplines with which the variables are most closely aligned.

### Atmosphere

Because major GHGs have atmospheric lifetimes of decades or more and so are rather well mixed, long-term GHG observations for the purposes of monitoring climate impacts can be made at coarse spatial resolutions. So integrated signals of emissions can be obtained over large areas, they should, however, preferably be conducted within “background” or pristine environments. As such, along with coastal and high-latitude sites, mountain stations such as Mauna Loa in Hawaii and Jungfraujoch in Switzerland play an important role in characterizing global GHG concentrations. Global *in situ* monitoring efforts are currently coordinated by the World Meteorological Organization (WMO) under the Global Atmosphere Watch (<https://public.wmo.int/en/programmes/global-atmosphere-watch-programme>)

program. For a review of atmospheric chemistry observations at mountain sites, see Okamoto and Tanimoto.<sup>75</sup>

Observations of vertically integrated trace gas abundances (i.e., columnar amounts) can also be made with satellites, although horizontal resolution remains limited and satellite retrieval is more challenging over complex terrain.<sup>76</sup> Ground-based remote-sensing networks, such as TCCON (<http://tccon.caltech.edu/>) and NDACC (<https://www.ndaccdemo.org/>), also report total column data in addition to some information on vertical structure, but measurements are costly, and making and interpreting them require significant manpower and expert knowledge. Because mountains often host important conservation areas and can be affected by higher ozone levels than adjacent regions, Mills et al.,<sup>36</sup> noting the current underrepresentation of high-elevation areas, recommended that future monitoring strategies seeking to assess the effects of ozone on vegetation in mountains account for the distinctive characteristics of such terrain. Pepin et al.,<sup>12</sup> meanwhile, identified a need to monitor black carbon and other aerosols more widely in order to determine their dependencies on meteorological variables.

When coupled with mesoscale aerosol modeling, observations of vertical atmospheric profiles of aerosols, cloud, and wind by remote-sensing instrumentation located in valley bottoms can provide a powerful means by which the transport of aerosol pollution to high-mountain regions can be characterized.<sup>77</sup> Taking measurements along vertical transects, which can also provide information about the vertical variability of radiative fluxes and aerosol deposition, represents an alternative, complementary approach.

Given the high spatial variability of surface ozone and aerosols, high-elevation observatories are key for monitoring long-term variability and change. Again, *in situ* measurements are useful here because they can be made with high precision and traceability by instrumentation that can be operated and quality controlled in a straightforward manner. In addition, measuring in mountainous terrains generally avoids influences from local emission sources, and so the resultant data usually have high spatial representativeness. Incidentally, this relatively high representativeness of certain atmospheric mountain variables is in sharp contrast to the surface-related variables that are of relevance to the other spheres, for which complex topography induces considerable heterogeneity and associated lack of measurement representativeness. *In situ* atmospheric monitoring networks should ideally be complemented by ground-based and space-borne remote observations, which provide superior spatial representativeness and coverage. Combined *in situ* and remote networks are optimal in terms of cross-validation and calibration.

Station measurements of these and other standard atmospheric variables (e.g., air temperature, precipitation, barometric pressure, solar radiation, wind speed, and humidity) also contribute to studies of more local mountain environmental change (and change impact) in other disciplines, although the issues related to spatial representativeness and maintenance discussed earlier often arise. Although not mountain specific, some such measurements in mountains are collated and standardized via the Global Historical Climatology Network.

### **Cryosphere**

Although snow, glacier ice, lake ice, and permafrost are not unique to mountainous terrain, observing them there is often

particularly challenging — whether directly as a result of access difficulties or remotely as a result of their high spatial variability.

That said, using optical satellite imagery, monitoring mountain glacier extents is relatively straightforward, and global inventories of glacier outlines have been compiled.<sup>78,79</sup> Image catalogs with high frequency and spatial resolution are better suited for monitoring the more rapid seasonal variations in snow cover, although cloud cover remains a persistent challenge. The prototype of the European Space Agency's (ESA's) Climate Change Initiative (CCI) product on snow-cover extent (not currently available for download) provides data at 1 km resolution and daily frequency, cloud cover permitting. However, conditions can vary widely over such scales in mountains; a 1 km<sup>2</sup> domain centered on the summit of Mont Blanc, for example, spans >600 m elevation range, and so enormous variability in snow conditions would be expected within such a region.

Monitoring snow and ice thickness and/or mass is considerably more challenging.<sup>80</sup> Even the GCOS ECV requirement for snow water equivalent (SWE)—data with daily frequency at 1 km resolution—is unachievable with any currently orbiting satellite technology. The ESA's CCI SWE product, for instance, is based on passive microwave measurements and has 0.25° resolution, but it explicitly excludes alpine areas for technical reasons. Recently, however, the possibility of mapping mountain snow depths (from which one can reconstruct SWE by assuming density) with 1 km resolution by using satellite radar has been demonstrated.<sup>81</sup> Nevertheless, many mountainous applications often require data with higher spatiotemporal frequency, meaning that only distributed snow or glacier models—employing either simplified empiric schemes (e.g., temperature-index approaches) or full energy-balance calculations—currently provide a means by which these needs for more spatially and temporally “complete” information on SWE dynamics and glacier mass balance (and derived gridded melt estimates) can be met. However, whenever simulation tools are involved, additional uncertainty is inevitably introduced, especially in data-limited regions.

At the point scale, one can measure SWE *in situ* either by digging pits and measuring total snow depth and integrated density by using snow pillows or—more recently—by deploying cosmic ray sensors.<sup>82</sup> Statistical models can also be applied for predicting SWE from more easily obtained snow depth series, albeit naturally with greater uncertainty.<sup>83</sup> Laborious snow profiling remains indispensable for assessing avalanche hazard. Snow melt can be measured locally with lysimeters or estimated from temporal changes in SWE series, provided that sublimation can be accounted for. The traditional approach to measuring glacier mass balance, i.e., characterizing annual accumulation via snow surveys and ablation by using a network of stakes, also involves intense *in situ* efforts. The World Glacier Monitoring Service collates and disseminates standardized data pertaining to many mountain glaciers, and the Global Terrestrial Network for Glaciers acts as a further framework for international coordination.

As alluded to previously, GCOS only specifies SWE as an ECV but not snow melt (which was a “new” variable added). Evapotranspiration was also added because for hydrological and ecological applications alike, it is extremely useful to be able to separate snow and glacier ablation into their sublimation and melt components.

The thermal state of permafrost cannot be measured remotely but rather requires *in situ* monitoring in boreholes. Many *in situ* permafrost observations are compiled and provided by the Global Terrestrial Network for Permafrost. Airborne laser scanning and photogrammetry data for surface elevation changes and surface expressions of buried ice, as well as radar data for ice and debris cover thicknesses, can be gathered only occasionally and for limited areas but do provide useful information that can be combined with simulations of mountain cryosphere change.

The WMO's Global Cryosphere Watch takes on a range of tasks related to the management and stewardship of cryospheric data—both *in situ* and remotely sensed—including from many mountain sites and regions.

### Biosphere

Correlating measured features of the biosphere with environmental factors (e.g., temperature, moisture, or snow variables) in time and space is critical for accurately monitoring, understanding, and predicting mountain biodiversity patterns and associated processes. However, in ecological applications, obtaining sufficient co-variate (or predictor) datasets remains a major challenge. Interpolation and modeling are therefore often employed to fill spatial and temporal observation gaps associated with *in situ* observations.

Yet, although sophisticated spatial analyses and interpolation algorithms are increasingly routinely conducted or applied in cryospheric and hydrological applications,<sup>84,85</sup> more simplistic alternatives often remain common in ecological studies. Alongside issues related to the preferential local siting of stations (e.g., on generally flat terrain), this can be problematic because the resultant spatially continuous datasets might not necessarily capture features, such as temperature inversions, air stagnation,<sup>86</sup> cold air pooling,<sup>87</sup> or orographic effects,<sup>88</sup> that can affect the long-term persistence of clonal and cold-adapted plant species.

However, some of these relevant patterns can now be captured by remote sensing. For example, both Landsat 8 and MODIS enable the characterization of surface temperature, whereas the Tropical Rainfall Measuring Mission (TRMM), the Global Precipitation Mission, and x-band radars yield estimates of precipitation. That said, the current spatial resolution of the data captured by these sensors might not adequately depict the complex mosaic of topoclimate encountered in alpine zones above the treeline,<sup>51,89</sup> which can alleviate the impact of warming temperatures on high-elevation organisms.<sup>90</sup> Fortunately, unmanned aerial vehicles can now deliver thermal images with a spatial resolution (up to 1 cm), albeit over much more limited areas.

Intensive field campaigns still play a major role with respect to the measurement of “dependent” biotic variables of interest,<sup>91</sup> although certain vegetation properties (e.g., forest cover, vegetation structure, and proxies of vegetation productivity) can also now be routinely retrieved from satellite-derived data from the normalized difference vegetation index (see Randin et al.<sup>92</sup> for an extensive review). Mountainous sites belonging to the International Long-Term Ecological Research Network, the GLORIA network, and, in the United States, the National Ecological Observatory Network are particularly relevant for monitoring the biosphere and associated aspects.

### Hydrosphere

As previously discussed, simply determining accurate spatial patterns of mountain precipitation remains a major challenge. Issues with the spatial distribution of precipitation gauges (spatial representativeness), systematic biases (e.g., due to wind-induced undercatch, especially when precipitation is solid), and topographic shadowing effects (in the case of radar estimates) all impinge on the accuracy with which this fundamental hydrological system input can be determined. Remote sensing precipitation would appear to be an attractive alternative. However, the reliability of these products (e.g., CMORPH [Climate Prediction Center morphing technique] and TRMM) is often questionable in mountainous terrain,<sup>93</sup> and their spatial resolution is also relatively coarse. Distinguishing the precipitation phase is also crucial, but this task is complicated by the fact that rain-snow temperature thresholds vary considerably on large spatial scales.<sup>94</sup> Recent trends in the general use of remote observations in hydrology are thoroughly reviewed by McCabe et al.<sup>95</sup>

Although continuous stream discharge is routinely measured *in situ* some distance downstream of many mountain regions globally, gauging stations are much rarer along lower-order (or headwater) streams, especially in developing countries. In addition, discharge measurements are often subject to considerable uncertainties at both high and low flows, especially where channel geometries are unstable. This is because the punctual flow measurements that inform rating curves are generally made at only moderate flow levels. In turbulent mountain streams, salt-dilution gauging is the most reliable approach to measuring discharge (see, e.g., García Parra et al.<sup>96</sup>) but is labor intensive and provides only punctual measurements. Irrespective of the method, the accessibility of both discharge data and appropriate metadata remains inconsistent. That said, numerous discharge-gauging stations located in or near mountainous regions do feed relevant measurements into the Global Runoff Data Center.

Various environmental tracers, both passive and active, can be used to attempt to quantify catchment water residence times, separate hydrographs into their various source components, and provide other insights (see, e.g., Singelton and co-workers<sup>97,98</sup>). However, numerous assumptions that can complicate the interpretation of the data and limit confidence in the results generally must be made. Measuring stable water isotopes in several water bodies is often useful and has become particularly popular. However, these variables do not feature on the GCOS list of ECVs, perhaps in part because of the associated laboratory analysis costs.

Potential evaporation ( $ET_p$ ) can be estimated roughly with various empirical formulae, but these generally yield neither spatially distributed nor transient information. This issue can be overcome by the application of more physically based calculations (e.g., the Penman-Monteith equation) to spatially distributed, transient data (e.g., station interpolations). Either way, gridded actual evapotranspiration ( $ET_a$ ) must then often be subsequently calculated by some form of model, typically as a function of atmospheric demand (i.e.,  $ET_p$ ), soil moisture conditions, and vegetation properties. Remote sensing does offer  $ET_a$  retrieval possibilities, but terrain complexity again poses some problems.<sup>99</sup> Quantifying sublimation, both *in situ* and remotely, is yet more challenging. Consequently, atmospheric losses

(i.e., actual evapotranspiration and sublimation) are often the most poorly constrained component of the water balance of many mountainous catchments. Unfortunately, above all in water-limited regions, these losses can be considerable with respect to incident precipitation.

Time-domain reflectometry represents the traditional option for measuring soil moisture *in situ*, although the spatial “support” of the corresponding data is normally extremely limited. Opportunities to remotely estimate surface soil moisture conditions are increasing, but their coarse spatial resolution remains an issue in areas of rugged topography. Generally speaking, more intense and comprehensive monitoring of land-atmosphere interactions in such regions (see, e.g., Ma and co-workers<sup>100</sup> and van den Bergh and co-workers<sup>101</sup>) could prove many valuable insights.

Groundwater monitoring networks require the installation of heavy machinery and are thus extremely sparse at high elevations. As a result of considerable subsurface heterogeneity (in both bedrock and unconsolidated sediments), the water-table-level records that do exist frequently suffer from limited spatial representativeness. Current records are too few and sparse to permit the analysis of groundwater level trends, for instance. Developing spatially integrated estimates of subsurface phenomena, such as MBR or total or dynamic (i.e., the component that contributes to streamflow) catchment groundwater storage, directly from data is challenging (but see Arnoux and co-workers<sup>102,103</sup>), although such estimates are often in high demand. Simulation-based approaches—especially fully integrated surface-subsurface modeling—provide an alternative option to quantifying mountainous water balances in a physically based, spatially explicit fashion.<sup>104,105</sup>

Sites belonging to the Critical Zone Exploration Network, many of which are situated in mountains, take an interdisciplinary but often somewhat hydrologically focused approach. The Global Terrestrial Network for Hydrology is another relevant but again non-mountain-specific initiative of note from a hydrological perspective.

### Emerging and future possibilities

In addition to these relatively established approaches, numerous emerging or future initiatives that could facilitate the measurement, derivation, or application of EMCVs are now emerging. Four specific themes—which together deal with *in situ* data, remotely sensed data, and their integration—are presented.

#### Long-term *in situ* observatories

The above discussion has demonstrated that, although many *in situ* variables are currently rather poorly observed (especially in less populated or developed mountain regions), *in situ* observations of EMCVs will undoubtedly remain a critical component of any future strategy. Because even more common variables, such as temperature and precipitation, suffer from networks with incomplete spatiotemporal coverage and elevational representativeness, extending existing and establishing entirely new mountain observatories and transects or extending existing ones will be important.<sup>106</sup>

Two complementary approaches could be taken. First, new high-quality mountain reference observatories could be established to facilitate the measurement of a wide range of EMCVs. Consistent with the spirit of this article, close collaboration and coordination between various authorities, researchers, and

practitioners with different backgrounds would be required. Existing interdisciplinary observatories that could be considered “models” range from those confined to single summits, such as the Jungfrauoch High Altitude Research Station in Switzerland (<https://www.hfsjg.ch/en/home/>), to those that cover entire mountain massifs and contain multiple transects or observation sites, such as the Niwot Ridge Long-Term Ecological Research Program in the United States (<https://nwt.berkeley.edu/>) and the Sonnblick Observatory in Austria (<https://www.sonnblick.net/en/>; Figure 3).

Such observatories often develop over many decades, leading to the availability of excellent, long-term records that are crucial for estimating any temporal lags between changes in forcing and system responses; for example, rapid climate change is expected to cause a severe disequilibrium between climate and vegetation species distributions as a result of slow colonization of newly suitable high-elevation areas and delayed extinctions in zones that are no longer suitable for low-elevation species—so-called extinction debt.<sup>107</sup> In practical terms, more interdisciplinary approaches to *in situ* measurements could reduce infrastructure installation and operation costs.

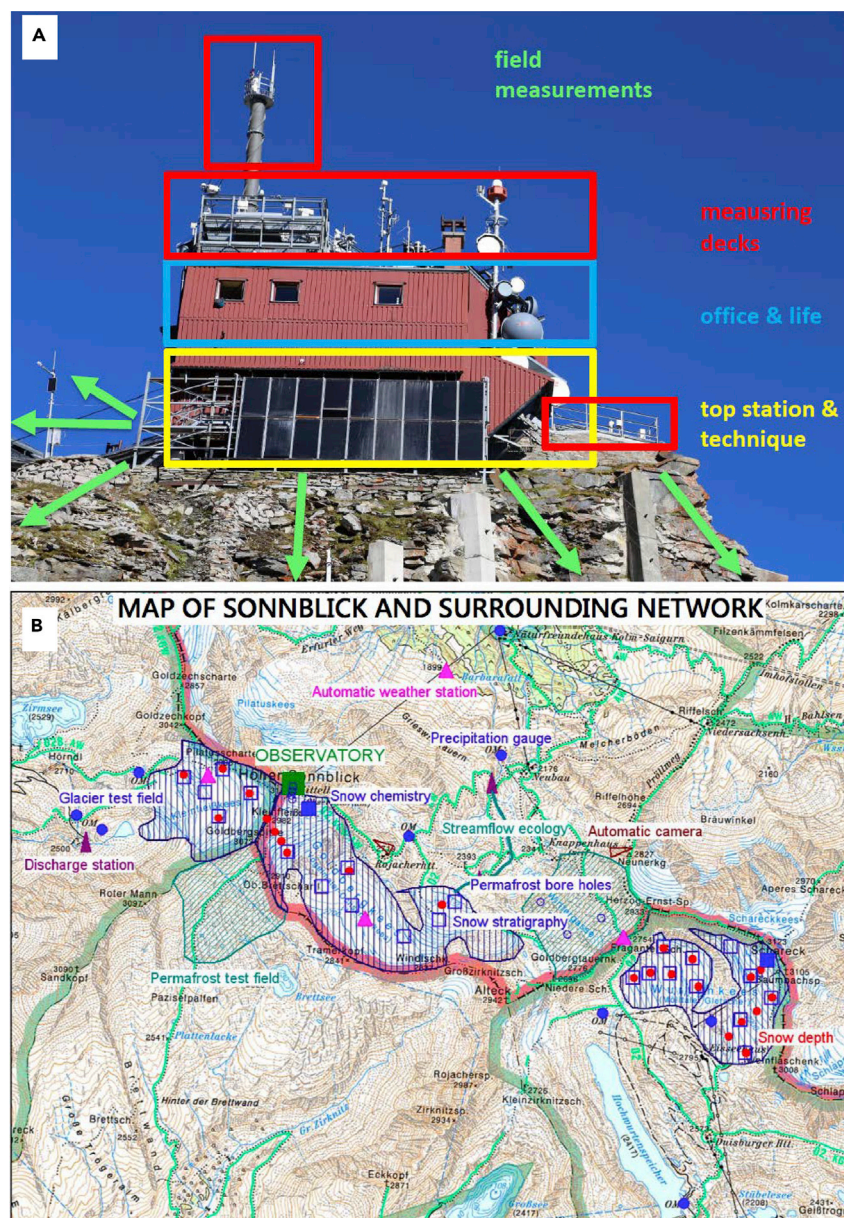
Given that different EMCVs can have contrasting ideal network configurations, a second approach could involve designing networks specifically to obtain richer information on the spatiotemporal variability of individual variables, such as air temperature or snow cover. One proposal in its early stages relates to the Unified High-Elevation Observation Platform, which aims to establish protocols for monitoring climatic variables along elevational transects. The concept proposes that it could be most expedient to combine high-quality “WMO standard” observations at a few “anchor” sites with a broader network of lower cost sensors distributed across the landscape at “float” sites—the latter of which capture more of the spatial variability. In mountainous terrain, elevational gradients will naturally often be the most conspicuous features of such network. However, ideally, contrasting topographic exposures, aspects, and slope gradients should also be systematically embedded within the wider network design<sup>108</sup> and accounted for in data analyses.

#### High-resolution satellite-based Earth observation

Satellite-based products constitute another important potential source of EMCV data. Currently, a large fleet of optical and radar satellites provide a constant, open, and accessible stream of data with high spatiotemporal resolution and wide geographical coverage. The Sentinel family of the European Union’s Copernicus program (<https://www.copernicus.eu/>), for instance, offers optical data (Sentinel 1) at 10–20 m resolution with a repetition rate of 3–5 days and radar data (Sentinel 2) at 2 m resolution every 6 days. NASA’s long-running Landsat (30 m resolution with biweekly coverage) and MODIS (moderate, i.e., 250–500 m resolution depending on the band with daily coverage) programs complement the European datasets.

Not least because the concept remains to be formalized, a thorough analysis of the extent to which any identified requirements can presently be met (by data from not only remotely sensed but also *in situ* sources) could not be conducted in this article. Nevertheless, many portals such as the Copernicus Climate Data Store (<https://cds.climate.copernicus.eu/#/home>), the ESA’s CCI Open Data Portal (<http://cci.esa.int/data>), and the MODIS portal (<https://modis.gsfc.nasa.gov/data/dataproduct/>)





**Figure 3. The Sonnblick Observatory and surrounding measurement sites in the Austrian Alps (originally built in 1886)**

The observatory belongs to broader (even global) numerous networks and makes its data freely available for download. Such an integrated environmental observatory, comprising a central hub (A) and distributed outlying sensors (B), could act as a model for the establishment of new or the extension of existing mountain observatories with a view to measuring EMCVs in other global mountain regions. Source: <https://www.sonnblick.net/en/> (reproduced with permission).

CCI portal provides data for variables with names corresponding to our potential EMCVs (see Table S1). The portal was found to provide some data for (only) 24 of 97 potential EMCVs. This further emphasizes that even if all these datasets are entirely suitable for mountainous applications—and of course many might not be (i.e., not all might meet EMCV observation requirements once these are eventually defined)—*in situ* observations are still needed to complement remotely sensed products.

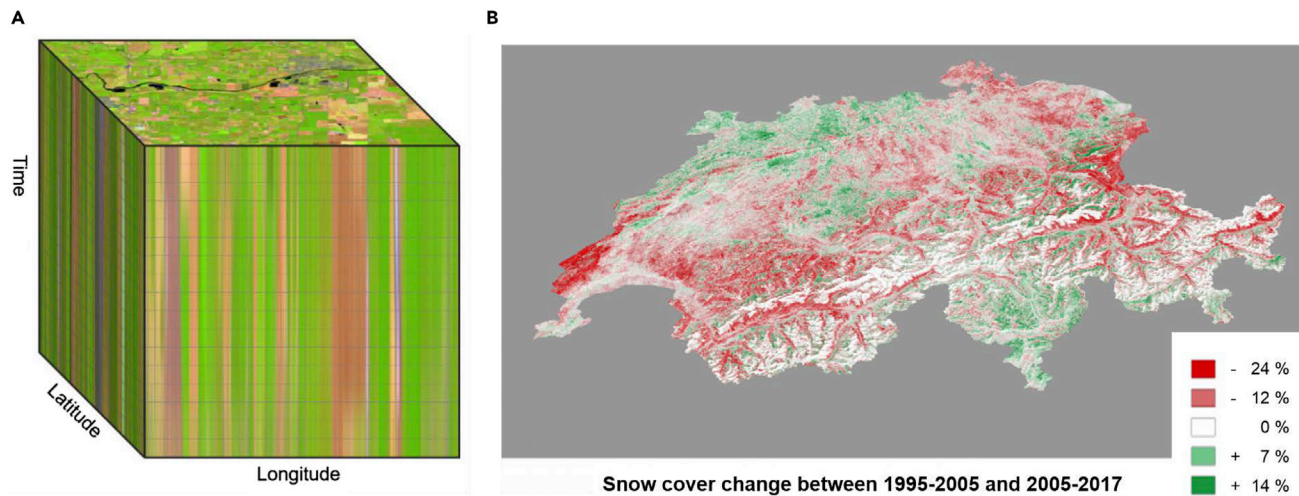
Recently, Earth observation data cubes (EODCs) (Figure 4) have emerged as another valuable method for generating new insights and knowledge from remotely sensed data.<sup>109</sup> With this approach, large amounts of analysis-ready data (ARD)—that is, data for which all necessary pre-processing (atmospheric and geometric corrections and conversion to surface reflectance in the case of optical data) has already been done—can be efficiently created<sup>110,111</sup> and transformed into information products that are of relevance to end users seeking to report on progress toward various global policy frameworks (see, for instance, Dhu et al.<sup>112</sup>). Compared with traditional workflows involving remotely sensed data, this solution relies

on interoperability, widely adopted standards, and open and replicable methodologies and can ultimately enhance the discovery, access, and use of Earth observation (EO) data.<sup>113,114</sup> Indeed, interoperability has previously been identified as a major issue that must be overcome if effective services are to be delivered on the basis of ECVs.<sup>115,116</sup>

For mountain research specifically, the global coverage and regular repeatability of remote-sensing products in general and of EODCs more specifically can help overcome the relative scarcity of *in situ* data. For example, an EODC integrating 34 years' worth of data was recently used to monitor changes in snow cover in the Italian Alps.<sup>118</sup> An additional attraction of EODCs is that, once developed, the methodologies can be directly applied to other regions. Currently, tens of EODC instances are either operational or under development, including in numerous

provide standard remotely sensed data that could meet some EMCV needs. For example, data can be obtained on snow cover, glaciers, soil moisture, and leaf area index (a widely used proxy for vegetation productivity). However, because for the most part these relatively long-term products are not yet derived from the latest instruments, their spatial resolutions are often only moderate, which could be insufficient for certain mountainous applications. Thus, to support high-quality EMCV data, the full potential of high-resolution Sentinel data available from 2015 onward must be exploited. This could involve developing methods (e.g., downscaling approaches) to improve refine the spatial resolutions of existing moderate-resolution on the basis of Sentinel data, thereby generating lengthier high-resolution catalogs.

To provide some initial indicative information, a simple assessment was undertaken to establish the extent to which the ESA's



**Figure 4. A representation and application of a data cube**

A generic data cube, i.e., an internally consistent collection of EO images for a given spatiotemporal domain (A) (source: Kopp et al.<sup>117</sup>), and an application of the Swiss Data Cube to assess snow-cover changes over time (B) (source: Dhu et al.<sup>112</sup>).

mountainous countries such as Switzerland, Austria, Armenia, Chile, Kenya, and Vietnam.

Looking further ahead, via an EODC that integrates data from Sentinel-5P<sup>119</sup>—a Copernicus program satellite designed for atmospheric monitoring at high spatiotemporal resolution—it should be possible to efficiently track black carbon and hence better monitor this potential contributor to EDW.

Finally, from the perspective of policymakers, combining the concepts of EODCs and E(M)CVs<sup>120</sup> can help to narrow information or knowledge gaps by providing insights that are synoptic, consistent, spatially explicit, sufficiently detailed to capture anthropogenic impacts, and increasingly transboundary and that cover sufficiently long time frames for determining trends, defining present conditions, and informing future actions.<sup>121,122</sup>

#### Climate-model reanalyses and future projections

Reanalyses are global or regional numerical weather model simulations into which observations from a range of sources are continuously assimilated. The resultant products therefore represent physically consistent “best estimates” of the historical state of the three-dimensional atmosphere and the land surface. Being gridded, they have “complete” spatiotemporal coverage and—like remotely sensed products—have considerable potential to complement traditional observational networks to improve our understanding of climate processes in remote, poorly observed mountain regions. More specifically, they provide consistent information on atmospheric variables that are not directly available from traditional monitoring networks or remote sensing, including in regions without traditional observational networks. They also allow surface process changes that can be observed *in situ* to be associated with the underlying climatic drivers (see, e.g., Forsythe et al.<sup>123</sup>).

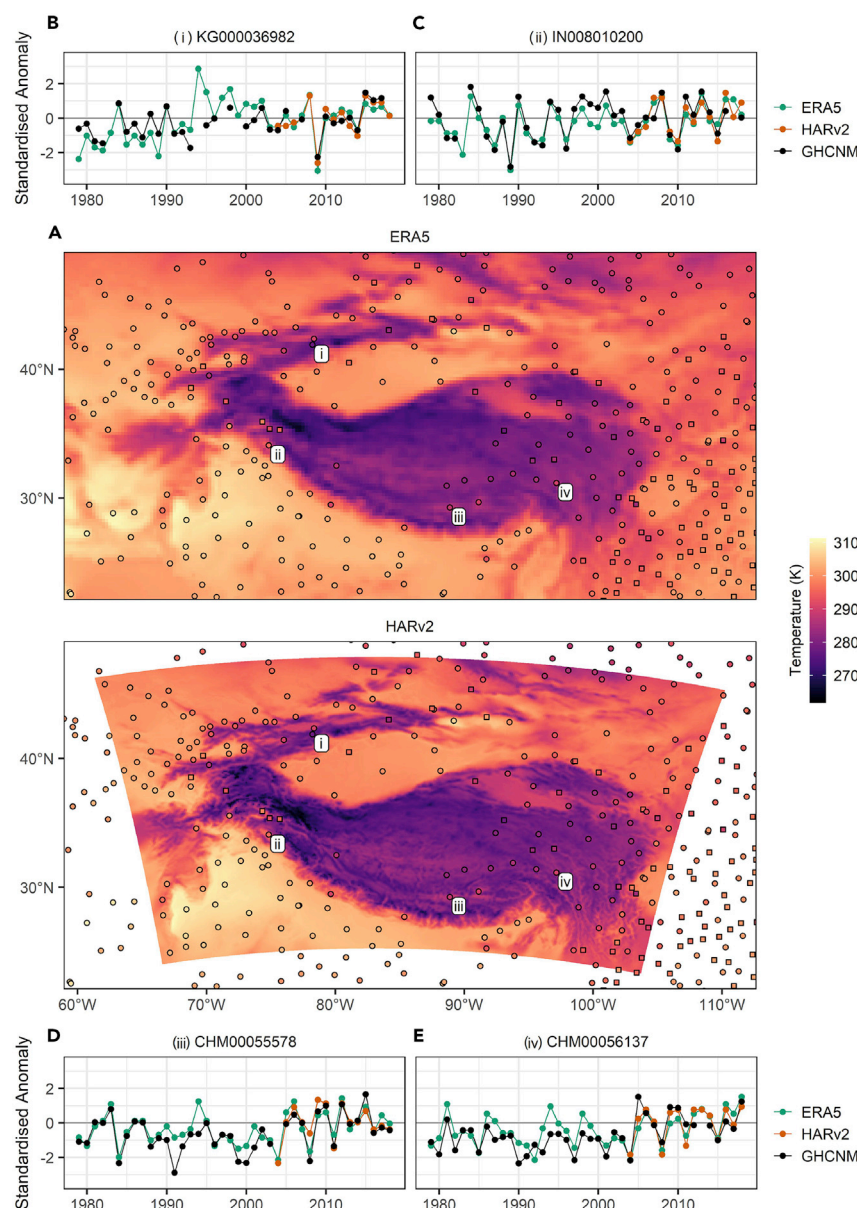
For applications in mountainous terrain, however, the spatial resolution of global reanalysis products is often too coarse for mountain-specific climatic features, such as mesoscale circulation characteristics, the influence of topography, and spatial vari-

ability in land cover to be resolved. That said, recently developed regional reanalyses are reducing this scale issue (see, e.g., Bollmeyer and co-workers<sup>124–126</sup>) and could represent an important—although not yet fully exploited—contribution to the derivation of EMCVs (see, e.g., Pritchard et al.<sup>127</sup>). For example, Figure 5 shows the spatial distribution of summer (JJA) near-surface air temperature, averaged over the period of 2004–2018, across high-mountain Asia according to two reanalysis products: ERA5 and HARv2.<sup>128</sup> The figure illustrates that such novel model-based reanalysis products are resolving topographic influences increasingly well and, even in relatively data-sparse mountainous regions, can generally capture both spatial and temporal variability well with respect to *in situ* observations.

Similarly, climate models, particularly at convection-permitting (<4 km) resolutions,<sup>129,130</sup> can mitigate both observational and knowledge gaps, especially with respect to climate variability and change, including those related to possible elevational dependencies.<sup>131</sup> Such hindcast models thus represent a valuable means by which existing datasets can be augmented and homogenized. They can, however, be subject to systematic and sometimes substantial biases that must be accounted for in subsequent applications.<sup>132</sup> Also, reanalyses products are generally released with a delay of several months rather than being updated in (near) real time (“timeliness” is an important factor in some applications). Traditionally, at more local scales, physics-based atmospheric, glacier, snow, and hydrological models can be forced with reanalysis products (see, e.g., Lundquist et al.<sup>133</sup>) to generate historical datasets pertaining to key state variables, some of which can act as inputs or predictors to models in other disciplines. EMCV data derived from *in situ* measurements find important applications in informing, constraining, and evaluating such models.

Climate-model projections that extend into the future under so-called representative concentration pathways are likewise critical to the generation of climate service products, such as regional or local climate change projections in mountain settings.





**Figure 5. A demonstration of the potential of recent climate reanalysis products**

Mean summer (JJA) near-surface air temperatures across high-mountain Asia correspond to the period 2004–2018 according to the ERA5 and HARv2 reanalysis products (A). Corresponding mean temperature values from the Global Historical Climatology Network-Monthly (GHCN-M) (v.4) *in situ* stations are also plotted (as circles where data are available for the same period; as squares otherwise). The inset figures (B–E) show time series of annual summer standardized temperature anomalies from four selected GHCN-M stations and the corresponding reanalysis product grid cells.

mitigated. Such limitations include the fact that *in situ* measurements are generally limited to point locations, satellite-based EO products are prone to data gaps and inaccuracies, and numerical models introduce various uncertainties in diverging from pure empiricism.

The precipitation MSWEP product<sup>135</sup> is an example of an output that already takes such an approach (see also Yin et al.<sup>136</sup>). Schattan et al.<sup>137</sup> and Thornton et al.<sup>138</sup> both incorporated remotely sensed and *in situ* snow data into the calibration of distributed snow models. Somewhat similarly, Podsiadlo et al.<sup>139</sup> combined *in situ* measurements of glacier mass balance with remotely sensed multi-spectral imagery (including from Sentinel 2) and topographic information to improve distributed estimates of glacier mass balance made by the AMUNDSEN model for a few alpine glaciers (Figure 6). Meanwhile, the ESA's CCI Permafrost project aims to produce global maps of active layer thickness by driving permafrost models with time series of remotely sensed land surface temperature.

The specific case of data assimilation, which was mentioned in the previous sub-section on reanalysis, involves making

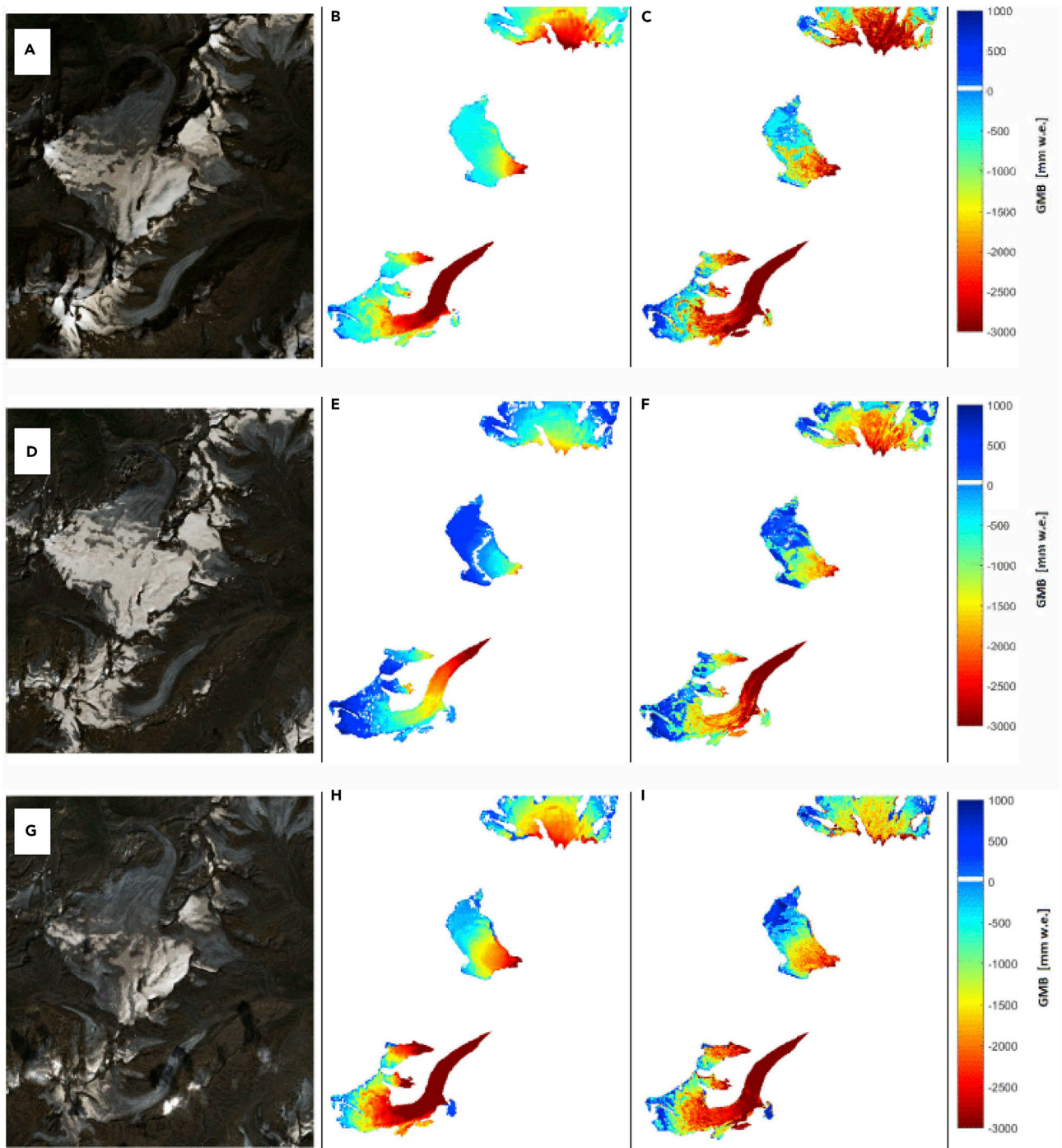
Such projections ultimately inform climate policy and adaptation measures. Here, observations play a particularly crucial role in selecting, weighting, bias adjusting, and further downscaling the outputs of climate models. The CH2018 Climate Scenarios for Switzerland, for instance, draw upon a range of observational networks and data sources to translate raw climate model output into robust and actionable climate service products.<sup>134</sup>

### Integrating diverse datasets into models

As has already been partially alluded to, the combined use of *in situ* data, remotely sensed EO data, and numerical models—not only for cross-validation but also for actual integration via calibration, data assimilation, or machine learning—offers numerous attractions and possibilities. Essentially, through such approaches, the benefits of the various techniques can be leveraged while their respective limitations are simultaneously

ing a statistically optimal merger of modeled and observed states (accounting for the uncertainty in both) to estimate involvement of atmospheric or land surface states. This approach is increasingly applied in snow modeling.<sup>140</sup> Observations from sparse *in situ* networks have large spatial uncertainties in complex mountain landscapes, however, can restrict their influence in data assimilation.<sup>141</sup>

A potential detraction associated with such approaches is that the distinction between raw empirical observations and model outputs (or other derived products) could become less clear. Establishing a series of EMCV data “levels” ranging, for instance, from 0 (“raw observations”) to 4 (“numerical model outputs informed by both *in situ* and remotely sensed data”) could provide useful clarification in this regard.



**Figure 6. Illustration of a data fusion approach to improve distributed estimates of glacier mass balance**

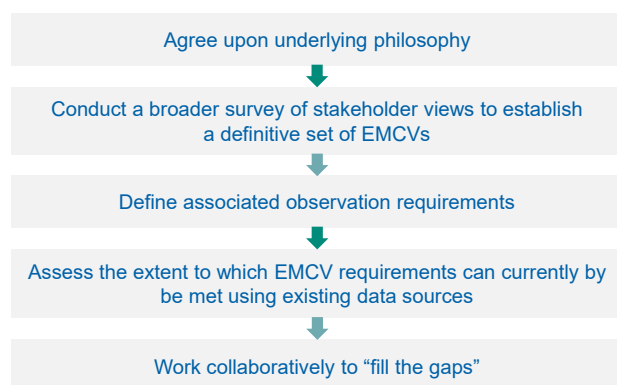
Summer true-color composite images from Sentinel-2 for three glaciers in the Ötztal Alps, Austria, for 2015 (A), 2016 (D), and 2017 (G); original AMUNDSEN-simulated glacier mass balance (GMB) (in mm water equivalent) for the corresponding years (B, E, and H); and improved AMUNDSEN-simulated GMB (in mm water equivalent) (C, F, and I). Source: modified after Podsiadlo et al.<sup>139</sup>

## SUGGESTED NEXT STEPS

Numerous additional (and potentially iterative) steps must be undertaken if the concept is ultimately to become formalized (Figure 7).

Firstly, through further discussion among researchers, practitioners, and policymakers, the philosophy underpinning EMCVs should be further debated and agreed upon. In particular, it must be decided whether the set of ECVs should aim to be rather extensive (i.e., include many variables) and/or “aspirational”





**Figure 7. A proposed “roadmap” toward the establishment of the concept of EMCVs and its eventual application**

(i.e., include variables that it might not be possible to measure and/or set demanding observational requirements) or whether it should rather be more pragmatic. A more pragmatic approach would most likely involve a more “distilled” set of variables, perhaps only those recognized as being absolutely imperative to a wide range of important questions or applications and/or that can be presently routinely measured in a cost-effective fashion in all global mountain regions.

The former approach, which has largely been advocated in this article, has the potential to stimulate investments and advances in observational technology, infrastructure, and methods such that it will eventually hopefully be possible to measure all the stipulated variables. The latter approach, meanwhile, which would be more akin to the position taken by the GCOS with respect to ECVs globally, has the obvious attraction that the data needs should be attainable more easily, which would enable a more prompt integration and comparison of a globally consistent set of observations. In general, however, the set should be as parsimonious as possible but as comprehensive as necessary, and—as noted above—in our view it should not be limited to purely empirical data.

Conducting a broader survey with a view to developing a ranking that is more representative of all relevant mountain disciplines and geographical regions would be another appropriate step. A wider range of stakeholders engaged in mountainous contexts, including researchers, environmental managers and practitioners, governmental representatives, representatives of non-governmental organizations, and the like, should be involved to ensure that diverse disciplines and their attendant perspectives, including those that might have been somewhat overlooked to date (e.g., aquatic ecosystems and nutrient and carbon cycling), are accounted for in confirming a final set of EMCVs. Established best practices in relation to survey design and execution should be employed to ensure that any potential biases are minimized and that the results are interpretable in a quantitative sense. If desired by the community, an “importance” threshold, perhaps with a pre-defined level, could be applied to the resultant ranking to clearly separate variables into the “essential” and merely “nice to have” categories.

A major factor motivating this article was the recognition that, although many variables stipulated by GCOS as being essential

in a global sense are also likely to be critical in mountains, their observation requirements in mountainous contexts will often be markedly different. Put simply, because of high spatial variability in the underlying processes, which is driven by pronounced terrain-driven gradients (steep, rugged terrain) and strong energy contrasts at various timescales (e.g., seasonal, diurnal), along with other short-lived phenomena (e.g., convective storms), the spatial and temporal resolution requirements are generally likely to be considerably higher in mountains than elsewhere.

Although some remarks proposing very general observation requirements for certain variables have already been made (for instance, whether spatial information is required or, in the case of key greenhouse gases, whether variables should be measured *in situ* or via remote sensing to provide column-integrated data), in the slightly longer term, carefully defined minimum observational requirements, such as spatiotemporal resolution, spatiotemporal coverage, timeliness, accuracy or uncertainty quantification, and so forth, must be thoroughly established for each EMCV. In this way, any data subsequently obtained should be useful for a wide range of general applications. As far as is possible, clear distinctions between the variables themselves and their associated requirements should be maintained. For instance, atmospheric temperature lapse rates and orographic precipitation gradients should arguably not be entirely new variables, as introduced here, but rather EMCVs that can be derived from temperature and precipitation measurements made according to appropriately specified standards (i.e., at several locations along elevational transects). However, these crucial tasks are unlikely to be straightforward.

Ultimately, it should prove possible to assess the extent to which EMCVs and their associated observation requirements can currently be met by existing data sources, providers, and networks more thoroughly and systematically than has previously been possible (see, e.g., Table S1). The most critical or pressing gaps can then be identified, and finally, opportunities can be pursued to close them.

## CONCLUSIONS

This perspective article has described some initial steps that have been undertaken toward establishing a set of interdisciplinary variables that could form observation priorities in mountainous terrain. The concept is intended to provide much-needed structure to the design and implementation of environmental monitoring and data-generation strategies across the world’s mountains. It is hoped that this in turn will not only contribute to substantial improvements in the understanding and prediction of climate-driven changes in such regions but also support sound decisions related to sustainable development, adaptation, and risk mitigation. Via an interdisciplinary review, the primary system components and processes involved in climate-related mountainous change in mountainous settings were first identified. Then, a set of corresponding potential EMCVs, ranked in order of perceived importance, was compiled.

Compared with the existing, more general notion of ECVs, our new concept is associated with several advantages. For example:

- Certain ECVs have little relevance in mountains and should therefore not be prioritized for measurement in such terrain (incidentally, the converse is true for some EMCVs in flat or lowland areas).
- Attention is drawn to variables that are considered important for monitoring and understanding mountainous environmental systems but that are not currently considered in a broader sense (i.e., are not ECVs).
- ECVs are largely grounded in empiricism and remote sensing, yet such approaches and technologies cannot yield meaningful information for all climate-related variables that could be important in mountainous areas; in this sense, the EMCV concept is more flexible in that it acknowledges the complimentary value of *in situ* data, remotely sensed data, and “blended” data-model approaches on more equal terms.
- ECV observation requirements with respect to spatial resolution and other measurement attributes or standards might be insufficient to ensure that the corresponding data are useful for applications in mountainous contexts; the EMCV approach thus allows these unique requirements to be specified.

Several more specific conclusions can be drawn. Firstly, and unsurprisingly given diversity and complexity of such systems, many variables seem to be required for characterizing such systems to some fundamental level. Measuring or otherwise generating informative data relating to all of these variables will undoubtedly be extremely challenging and will most likely require the development and application of novel observation and simulation technologies across (and between) all disciplines. Secondly, and also naturally enough, those variables that hold relevance across several spheres, such as surface albedo, precipitation, and air temperature, featured highly in the ranking.

Although some important mountain variables can evidently now be retrieved via remote sensing—indeed, remote sensing offers excellent possibilities to derive variables related to the land surface and energy balance, which often act as “linkages” between disciplines—it is equally true that many variables can still only practically be measured *in situ*. Certain other variables, such as spatially integrated fluxes and storages pertaining to the subsurface of the hydrosphere, can only be derived from model simulations.

The identification of several variables that are not currently listed as ECVs as being important in mountainous contexts represents an important outcome. Some of the variables identified as being especially important in mountainous areas that do not currently feature in the GCOS ECV set could in fact arguably also hold wider relevance and so could perhaps be considered for future inclusion by GCOS. Specifically with respect to mountains, however, it can be suggested that:

- Consistent observations of atmospheric variables related to a rather wide range of gas concentrations and pollutants or factors related to air quality are required in mountainous regions for monitoring and understanding the radiative fluxes that can profoundly affect many aspects of the broader system, especially components of the biosphere and cryosphere.

- Improved monitoring of the mountain biosphere requires detailed monitoring and mapping of species abundances, extents, and perturbing factors that go beyond the scope of the GCOS ECVs.
- Although some aspects of the mountain cryosphere are increasingly well monitored and mapped via remote sensing (and are largely already included as ECVs), certain more specific variables, such as snow microstructure and debris cover, are not; such variables are required, however, for improving the remote sensing of mountain snowpacks and understanding glacier changes.
- Topographic variables and variables characterizing climate-related natural hazards, which are not currently considered ECVs, are crucial to most scientific, policy, and practice-related work in mountainous terrain.

The discussion furthermore illustrated that for the observation of certain atmospheric variables, mountainous sites are attractive precisely because—being generally distant from emissions sources and high in the troposphere—they allow “background” levels to be reliably characterized. As such, mountain-based monitoring of such variables is important not only with respect to local impacts but also in a more general, global sense. In these cases, existing ECV requirements could largely suffice. The situation here contrasts greatly with that of many of the more surface-influenced variables of other spheres, which generally display considerable heterogeneity so require high-resolution monitoring.

Finally, we suggest that simulation-based approaches provide an attractive means by which historical datasets can be enriched in order to generate consistent and high-quality EMCV datasets retrospectively, which is another vital task. Accordingly, it is proposed that EMCVs need not be limited to strictly empirical observations (as per ECVs) but should rather also encompass “derived datasets” that are generated, for instance, via the integration of *in situ* data, remotely sensed data, and numerical models. The provenance of the outputs should always be clearly labeled, however.

This contribution has primarily focused on highlighting those variables that could most assist researchers, practitioners, and policymakers concerned with monitoring and understanding change process and impacts at comparatively local scales (i.e., within and immediately downstream of mountain regions). A comprehensive review of existing networks and associated datasets was not intended here. Large-scale interactions and feedbacks between mountainous regions and the wider global climate and Earth system are of potentially considerable significance but also highly uncertain. In any case, taking such a larger-scale view falls beyond the current scope. It should, however, form a focus of future scientific efforts. Indeed, if the envisaged global database of EMCVs can be constructed, it should provide an extremely useful resource to help address many open questions regarding the role of mountains in large-scale atmospheric teleconnections and global feedbacks. Considering in detail the generation of future environmental predictions under altered climatic conditions was also not our focus here, although the simulation approaches mentioned generally also have this capability.

Efforts to monitor mountain biodiversity in detail could be associated with highly specific requirements. In addition, in many mountain regions, natural systems (that have been



**Figure 8. Photographs from the interdisciplinary workshop**  
The authors and workshop organizers do not endorse any particular manufacturer of outdoor clothing!

considered here) are intrinsically linked with complex socio-economic ones. For instance, anthropogenic activities also exert major and direct influences on mountain systems through grazing, forest management, hydraulic engineering, and infrastructure installation. As such, similar contributions regarding mountain biodiversity and socio-economic variables are planned, raising the prospect that a single, integrated set of essential mountain variables could eventually emerge.

Overall, this contribution intends to (1) stimulate further debate on the subject of collecting or generating more consistent and useful datasets by and for the mountain research community and (2) set a sequence of future activities in motion. Through its ongoing activities related to enhancing the discoverability, accessibility, and usefulness of a wide variety of data pertaining to mountains, GEO Mountains hopes to contribute to this and many other important tasks.

## EXPERIMENTAL PROCEDURES

### Resource availability

#### Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the corresponding author, James M. Thornton ([james.thornton@unibe.ch](mailto:james.thornton@unibe.ch)).

#### Materials availability

This work did not generate new unique materials.

#### Data and code availability

The code and data required for reproducing Figures 2 and 5 are available at <https://doi.org/10.5281/zenodo.4741927>. No other original data were used, and no additional processing tasks were undertaken in the preparation of this manuscript.

### Interdisciplinary workshop

This work was developed from discussions held during a workshop entitled “Essential climate variables for observations in mountains.” The workshop was organized under the auspices of GEO Mountains (the GEO’s Global Network for Observations and Information in Mountain Environments; formerly GEO-GNOME) and was hosted by the Mountain Research Initiative at the University of Bern, Switzerland. It took place June 24–26, 2019.

At the workshop, many of the co-authors gave invited presentations—based on their own disciplinary perspectives and areas of expertise—on what the most important system components and processes related to ongoing change might be, as well as the state of the corresponding “data landscape”.

The 18 participants then formed four thematic groups (atmosphere, cryosphere, biosphere, or hydrosphere) according to their expertise and interests but with the freedom to move groups at any point if desired. Each group was

assigned a moderator. Mindful of the content of the invited presentations, the groups discussed the key system components before proceeding to identify and rank associated variables according to their perceived importance (Figure 8).

The existing GCOS catalog of (global) ECVs formed the starting point for this process. Variables with little apparent relevance to the mountain processes under consideration could be disregarded, and additional variables could be added as required. Each group then arrived at a consensus as to the importance of each listed variable for system components and processes corresponding to the “sphere” they were considering. The following ranking scale was applied: most important (3), important (2), less important (1), and not important (0). In cases where the same (or essentially the same) variable was identified by more than one group, the scores for that variable were aggregated. Finally, after the workshop, we undertook a considerable amount of further synthesis, discussion, re-organization, and classification of the resultant material to produce more coherent and representative outcomes (e.g., Figure 2 and Table S1).

As stated above, the resultant ranking should not be considered in a strict, quantitative sense. The constitution of the participants could have caused greater emphasis to be placed on variables corresponding to their respective fields at the expense of those related to less well-represented disciplines (or sub-disciplines). In addition, the levels of importance assigned could have been interpreted differently by different individuals and/or groups (especially without their having considered practicalities, such as observation financing). In addition, the interpretations of the task, as well as certain processes and corresponding variables, could have differed between individuals or groups. For these reasons, a more extensive and inclusive survey should be undertaken in the future. The nature of this workshop did have clear benefits, however: a free, discussion-focused format that was not limited to a strict, constrained process was favored.

## SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.oneear.2021.05.005>.

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